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FLIGHT INVESTIGATION OF THE LONGITUDINAL STABILITY AND CONTROL CHARACTERISTICS OF A FOUR-PROPELLER TILT-WING VTOL MODEL WITH A PROGRAMED FLAP

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SUMMARY

An investigation of the longitudinal stability and control characteristics, during slow constant-altitude transitions from hovering to forward flight, of a high-wing VTOL (vertical-take-off-and-landing) airplane model with a tilting wing and flap was conducted by a remote-control free-flight model technique. The model was a four-propeller configuration with a 35-percent-chord slotted flap that was programed to deflect as the wing rotated from 90° to 0° for transition from hovering to forward flight. The flap programing was arranged so that the flap was retracted for the 90° and 0° wing-incidence conditions to give a clean configuration for hovering and for normal forward flight. The flap was deflected for intermediate angles of incidence to obtain favorable performance and longitudinal trim characteristics for the transition flight conditions.

The flight tests showed that the transition could be performed and that by proper programing of the deflection of a full-span flap and the incidence of the horizontal tail, the variation of longitudinal trim throughout the transition range could be practically eliminated so that the control power remaining for maneuvering would not be reduced at any point in the transition. The model had an unstable pitching oscillation in hovering flight, but this dynamic instability decreased rapidly as the forward speed increased.

INTRODUCTION

In the past, flight tests of various tilt-wing vertical-take-off-and-landing airplane models have shown that they characteristically tend to develop a large nose-up pitching moment as the aircraft starts through transition from hovering to forward flight (refs. 1 and 2). This change in pitch trim with speed and wing incidence can severely limit the range of center-of-gravity positions for which it is possible to perform the transition successfully. Force tests of a tilt-wing-and-flap combination have indicated, however, that with proper programing of flap deflection with wing tilt, it is possible to design a tilt-wing VTOL aircraft in which essentially no change in trim is required throughout the transition from hovering to normal unstalled forward flight (ref. 3). A tilt wing with a programed flap has the additional advantage that for the intermediate angles of wing incidence, the flap is in a deflected position to make the wing carry as much of the load as possible in the transition range to minimize the power required and to give good STOL characteristics.

The investigation reported herein was made to check out the tilt-wing-and-flap scheme on a complete model designed to represent a tilt-wing VTOL transport airplane. A force-test investigation of this same model has been made and is described in reference 4. The flight investigation was conducted as a study of the longitudinal stability and control characteristics, but some observations of the more outstanding lateral characteristics were made and are included herein.

SYMBOLS

The forces and moments are based on the stability-axis system, which is an orthogonal system with the origin at the airplane center of gravity. The Z-axis is in the plane of symmetry and perpendicular to the relative wind, the X-axis is in the plane of symmetry and perpendicular to the Z-axis, and the Y-axis is perpendicular to the plane of symmetry.

$\bar{c}$ wing mean aerodynamic chord, ft

i_t horizontal-tail incidence, positive where trailing edge is down, deg

i_w wing incidence, deg

M_X rolling moment, ft-lb

$M_{X_\beta} = \frac{\partial M_X}{\partial \beta}$, ft-lb/deg

M_Y pitching moment, ft-lb

$M_{Y_\alpha} = \frac{\partial M_Y}{\partial \alpha}$, ft-lb/deg

M_Z yawing moment, ft-lb

$M_{Z_\beta} = \frac{\partial M_Z}{\partial \beta}$, ft-lb/deg

V velocity, ft/sec

α angle of attack of fuselage, deg

β angle of sideslip, deg

APPARATUS AND TESTS

Model

A photograph of the model used in the investigation is shown in figure 1. The model is a four-propeller tilt-wing VTOL configuration equipped with a 35-percent-chord slotted flap. A three-view sketch showing some of the more important dimensions is presented in figure 2, and the geometric characteristics of the model are listed in table I. The model was designed with the center of gravity on the thrust line in hovering flight so that no pitch-trim force would be needed. The variation of center of gravity with wing incidence is shown in figure 3, and the variations of the moments of inertia of the model with wing incidence are shown in figure 4. The model had four 3-blade propellers, each of which was powered by a pneumatic motor. The propellers were not interconnected, but the motors were all connected to a common manifold. A trimming valve by which the motor speeds could be synchronized, if necessary before the flights, was provided on each motor inlet. Calibrations showed, however, that the motors stayed in synchronization so well that it was only necessary to readjust the speed of a motor after it had been disassembled for maintenance.

The wing was pivoted at the 65-percent-chord station and could be rotated between incidences of 0° and 90° during flight by an electric motor. The 35-percent-chord slotted flap was programed with a simple cam and follower to deflect as the wing incidence changed. With the method used for the programing, it was possible to program the flap for only one type of transition; therefore, the flap angles used were for a very slow transition with the fuselage at zero angle of attack. The variation of flap angle with wing incidence is shown in figure 5.

Two types of ailerons were used during the tests. The original model configuration as shown in figure 1 had a conventional aileron which was used in conjunction with a partial-span single-slotted flap.

The second type of aileron was a slot-lip aileron and was installed on the model when, as a result of preliminary tests, the slotted flap was extended to full span (see fig. 2). The slot-lip aileron was created by hinging the outer 30 percent span of each slot lip. A typical cross section of the wing through the slot-lip aileron is shown in figure 6. The model also had a conventional rudder and an all-movable horizontal tail for aerodynamic control.

Control for hovering and low-speed flight was provided by means of jet reaction controls. Roll control in hovering was provided by a jet reaction control mounted on the left wing tip. For pitch and yaw control in hovering flight, the model had jet reaction controls that exhausted up or down and sideways at the rear of the fuselage.

The controls were deflected by flicker-type (full-on or off) pneumatic actuators that were remotely operated by the pilots by means of solenoid-operated valves. The aileron and pitch-jet control actuators were equipped with integrating-type trimmers that trimmed the controls a small amount each time a control was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition. It was found that yaw problems were induced when any trim put into the model in hovering could not be taken out fast enough when the wing tilted for transition; therefore, the roll-jet actuator was not provided with any trimmer. An electric trim motor was provided to enable the pilot to trim the model in yaw. The yaw jet and the rudder were both connected to a rate-sensitive artificial stabilizing device. This yaw damper consisted of a yaw rate gyroscope that provided signals to a proportional control actuator which moved the control surface to oppose the yawing motion. An override was provided which cut out the damper when the pilot applied control.

Test Equipment and Setup

The test setup used in the tests was essentially the same as that used for all transition flight tests in the Langley full-scale tunnel and is illustrated in figure 7. An additional operator (not shown in fig. 7) was located near the pitch pilot to control the wing incidence in these tests. The power for the wing-tilt motor, the yaw-trim motor, and the electric-control solenoids was supplied through wires; the air for the main propulsion motors, the jet reaction controls, and the control actuators was supplied through plastic tubes. These wires and tubes were suspended from the top of the tunnel and were taped to a safety cable (1/16-inch braided aircraft cable) from a point about 15 feet above the model down to the model itself. The safety cable, which was attached to the fuselage near the wing pivot, was used to prevent crashes in the event of a power or control failure or in the event that the pilots lost control of the model. Separate pilots are used to control the model in pitch, roll, and yaw since it has been found that if a single pilot operates all three controls in hovering, he is so busy controlling the model that he has difficulty in correctly ascertaining the stability and control characteristics of the model about its various axes. In forward flight at least two pilots are always needed.

Tests

The present investigation consisted almost entirely of transition-flight tests. The results were mainly qualitative and consisted of pilots' observations and opinions of the behavior of the model.

The transition flight tests were made in the Langley full-scale tunnel by starting with the model hovering (fuselage horizontal) in the test section at zero airspeed. As the airspeed was increased, the wing-tilt operator gradually reduced the wing incidence to maintain approximately the desired fuselage angle of attack during the transition. These flight tests covered a speed range from 0 to about 48 knots. Since small adjustments or corrections in the tunnel airspeed could not be made readily, the pitch pilot, wing-tilt operator, and power operator had to make adjustments continually to hold the model in the center of the test section.

The tests were made with the pitch jet providing a force equal to about ±5 percent of the model weight. The all-movable horizontal tail was not controlled by the pilots during any of the flight; therefore, the pitch jet was the only longitudinal control available from hovering to forward flight. The horizontal tail either remained fixed in one position or was programed with a mechanical linkage to move as the wing tilted in various tests.

Yaw control from hovering to forward flight was provided by the yaw jet (which provided a force of about ±4.9 percent of the model weight) and by the rudder operating together, since, as mentioned previously, they were connected to the same actuator. The model had a yaw damper installed to provide a high degree of lateral stability so that the longitudinal characteristics of the model could be more easily observed.

Roll control in hovering and low-speed flight was obtained by a jet reaction control mounted on the left wing tip. This roll jet provided a force of about ±6.4 percent of the model weight. At a speed of about 30 knots, the ailerons (either conventional or slot-lip) were switched in for roll control, but the tip jet remained operative to augment the roll control provided by the ailerons.

Only a few preliminary flight tests were made for the partial-span-flap configuration with and without the ailerons drooped. During these tests, it was deemed desirable to install the yaw damper which was used during the rest of the flight-test program. Certain stability and control problems were encountered in the initial flight tests that made it desirable to suspend, temporarily, the flight-test program and conduct some force tests on the partial-span-flap configuration to determine the source of the trouble. The results of these force tests are reported in reference 4. After the force tests, the flight tests were continued by using the full-span-flap configuration. Much more detailed observations were made of the stability and control characteristics during the tests made with the full-span-flap configuration than during those made with the partial-span-flap configuration.

RESULTS AND DISCUSSION

Longitudinal Stability and Control

Partial-span flaps.- The flight tests showed that it was possible to perform transitions with the partial-span-flap configuration with the ailerons not drooped and with the stabilizer fixed at 0° incidence. Only a few preliminary flight tests were made with this configuration, however, because the first flights showed that the partial-span flap was not performing the job for which it was intended - that is, during the transition, it was not trimming out the nose-up pitching moments which are characteristic of tilt-wing VTOL aircraft configurations. Specifically, it was found that this configuration experienced a decided nose-up change in trim as it started into the transition from hovering flight. The nose-up pitching moments used up a large percentage of the available jet reaction control, and the control power remaining for maneuvering was not entirely adequate. For this reason, the model occasionally nosed up out of control after it had been allowed to build up a higher nose-up pitching velocity than could be stopped by the pilot with the limited amount of control power remaining after trim. These flight-test results are, at least, in qualitative agreement with the results of the force tests which were made later. The force-test data taken from reference 4 are summarized in figure 8. This figure shows that in the most critical condition, $i_w = 60^{\circ}$, the model had a nose-up pitching moment of about 6 foot-pounds and the pitch-jet control power available to counteract this trim change during the flight tests was only about 10 foot-pounds.

After the initial flight tests of the partial-span-flap configuration with conventional ailerons undrooped where it was found that the flap did not eliminate the nose-up pitching-moment problem during the early part of the transition, it was decided to droop the ailerons 20°

to provide additional nose-down pitching moment in an attempt to alleviate the problem. In the flight tests with the drooped ailerons, however, the pitching-moment trim-change problem was still quite evident. This result is in agreement with the force-test data (summarized in fig. 9) which show that there was a large change in pitching moment with speed for the drooped-aileron configuration. Comparison of the force-test data for the drooped- and undrooped-aileron configurations did not indicate that the pitching moments were reduced by drooping the ailerons for the $i_t = 5^\circ$ condition covered in the force tests, and presumably would not have been reduced for the $i_t = 0^\circ$ condition covered in the flight tests.

Not only did the force-test data (summarized in figs. 8 and 9) indicate the existence of a large nose-up pitching moment with $i_t = 0^\circ$, but analysis based on these data indicated that it would not be possible to trim out this pitching moment even by the use of large positive tail incidences. The most critical condition as far as the trim problem was concerned occurred at such a low speed ($V = 17$ ft/sec at $i_w = 60^\circ$) that the maximum pitching moments which the horizontal tail could produce were very small - approximately 1.5 foot-pounds.

Full-span flap.- The first tests for the full-span-flap configuration were made with the horizontal tail still fixed at $i_t = 0^\circ$, as was the case with the previous tests. It was found that a substantial nose-up pitching moment was still experienced near $i_w = 50^\circ$. This result is in agreement with the force-test results which are summarized in figure 10 and which indicate that for $i_t = 0^\circ$ the maximum nose-up pitching moment would have been about as large as for the partial-span-flap configurations. These data also show that the condition for maximum nose-up pitching moment occurred at a higher speed ($V = 20$ ft/sec at $i_w = 50^\circ$). The data show, however, that the pitching moment was reduced considerably for the tail-off condition, and analysis of the data indicated that even for the most critical condition, the model could be trimmed by the use of about 25° tail incidence. For the remainder of the flight tests, the horizontal tail was programed with a simple mechanical linkage to deflect as the wing tilted. This tail programing, shown in figure 11, was arranged to give $i_t = 25^\circ$ in the critical range near $i_w = 50^\circ$ and was not tailored to be ideal over the whole range of wing incidences. Flight tests of the model with the programed tail showed that it was effective in eliminating the pitching-moment trim change throughout the low-speed portion of the transition range. The particular programing used, however, gave too much tail incidence in the higher speed portion of the transition range. For example, at $i_w = 20^\circ$, the plot of the variation of horizontal-tail incidence with wing incidence in figure 11 shows that the tail incidence was 15°, whereas the force-test data of figure 10 show that only about 5° tail incidence was needed. The pitching-moment problem therefore seemed to be reduced to the problem of obtaining the proper programing of tail incidence, which could not be done without constructing a more elaborate system for the model. The pitch-trim problem therefore was not pursued any further.

With the full-span-flap configuration the longitudinal stability and controllability of the model were observed in some detail. It was found that in hovering flight the model had an unstable control-fixed oscillation, as indicated by the time history for the hovering condition in figure 12. The period of this oscillation was reasonably long (3 to 3.5 sec) and the pilot could easily control the model with the control available (pitch jet force of ±5 percent of model weight).

As the transition was started, the unstable pitching oscillation became less evident. In fact, it was not even noticeable to the pilot when flying the model in the normal manner. The records of a control-fixed oscillation obtained from motion pictures and presented in figure 12 show, however, that the model actually had a slightly unstable oscillation. This oscillation had the very long period of about 7 seconds model scale; thus, without looking carefully for the oscillation, the pilot would not ordinarily distinguish it from the normal gusts or other disturbances that the model experiences in flight tests. The force tests of the model show that the model had about neutral static longitudinal stability in this condition.

The time histories of figure 12 show no unstable oscillation at $i_w = 30^{\circ}$. The record simply shows the model diverging slowly, evidently because of some out-of-trim moment. For this condition, force-test data of figure 10 show that the model was statically stable. The speed for this wing-incidence condition is about 40 feet per second, which is about one-half the power-off stalling speed of the model.

Lateral Stability and Control

As pointed out previously, this investigation was carried out primarily to study the longitudinal characteristics of the present tilt-wing configuration, but a few observations of the lateral stability and control characteristics were made and are reported in the following paragraphs.

In the hovering condition, no particular investigation was made of the stability characteristics of the model in roll and yaw. The rolling and yawing motions could be controlled quite easily, however, with the control power available.

It was observed in the preliminary transition flight tests (no rate gyro) that the model was directionally unstable to a slight degree throughout most of the transition speed range. This same result was shown in the force tests, a summary of which is shown in figure 13 taken from reference 4. It was also found in the flight tests that the model experienced a large change in yawing moment throughout the transition speed range. This result was also evident from the force tests and is shown in the summary figure, figure 14. The force-test data show that at $i_w = 50^\circ$, the yawing moment reached a maximum of about 5 foot-pounds, which is about one-half the magnitude of the available control moment. The force-test data of figure 13 also show that the directional instability was a maximum at this same point; thus, the problem was more difficult than would ordinarily be expected. In this connection, a tuft survey showed that there was a severe stall over the wing center section which at times, possibly because of wing asymmetry, extended over the inboard portion of the right wing. It is believed that this directional stability and trim problem is a peculiarity of this particular model and should not be considered characteristic of this general type of configuration. Because of the directional stability and trim problems, the yaw damper was installed in the yaw control system and was used throughout the remainder of the tests. Because of the stability augmentation provided by the damper, the natural stability characteristics of the model were obscured and so were not studied.

The force-test data of figure 13 show that the model had negative effective dihedral in the range from $i_w = 60^\circ$ to $i_w = 25^\circ$. This characteristic was not noted in the flight tests, however, evidently because of the small magnitude. The maximum negative dihedral effect was so small that it would require only about 2 percent of the available roll control to trim each degree of sideslip.

One point stood out with regard to lateral control during the flight tests - that the control power provided by either the drooped ailerons or the slot-lip ailerons was undesirably low in the high-speed part of the transition range. This point was also brought out by the force tests of reference 4 which showed, for example, that the rolling moment produced by these ailerons was less than one-half of that produced by the conventional ailerons.

CONCLUDING REMARKS

Flight tests of a model of a four-propeller tilt-wing VTOL airplane having a slotted flap programed to deflect as the wing tilted showed that transitions could be performed and that by proper programing of the deflection of a full-span flap and the incidence of the horizontal tail, the variation of longitudinal trim throughout the transition range could be practically eliminated so that the control power remaining for maneuvering would not be reduced at any point in the transition. T model had an unstable pitching oscillation in hovering flight, but is dynamic instability decreased rapidly as the forward speed incre until the model appeared to be completely stable by the time the speed was equal to about one-half the power-off stalling speed.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 12, 1962.

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2. Tosti, Louis P.: Flight Investigation of the Stability and Control Characteristics of a 1/4-Scale Model of a Tilt-Wing Vertical-Take-Off-and-Landing Aircraft. NASA MEMO 11-4-58L, 1959.

3. Newsom, William A., Jr.: Effect of Propeller Location and Flap Deflection on the Aerodynamic Characteristics of a Wing-Propeller Combination for Angles of Attack From 0° to 80°. NACA TN 3917, 1957.

4. Newsom, William A., Jr.: Force-Test Investigation of the Stability and Control Characteristics of a Four-Propeller Tilt-Wing VTOL Model With a Programed Flap. NASA TN D-1389, 1962.

TABLE I.- GEOMETRIC CHARACTERISTICS OF THE MODEL

Fuselage:	
Length, in.	84.8
Diameter (maximum), in.	10.4
Wing:	
Area, sq in.	1,002.25
Aspect ratio	9
Mean aerodynamic chord, in.	10.77
Airfoil section	NACA 65-210
Tip chord, in.	7.9
Root chord, in.	13.2
Span, in.	95
Taper ratio	0.6
Sweepback of 0.65 chord	0
Dihedral angle, deg	0
Pivot station, percent chord	65
Flap chord, percent wing chord	35
Aileron, conventional (each):	
Chord, percent wing chord	35
Span, percent wing semispan	30
Aileron, slot-lip (each):	
Chord, in.	0.75
Span, percent wing semispan	30
Vertical tail:	
Area (total to center line), sq in.	269
Aspect ratio	1.97
Airfoil section	NACA 0009
Tip chord, in.	5.4
Root chord (at center line), in.	18.0
Span, in.	23.0
Taper ratio	0.3
Sweepback (leading edge), deg	25
Rudder (hinge line perpendicular to fuselage center line):	
Tip chord, in.	2.5
Root chord, in.	4.05
Span, in.	14.03
Horizontal tail:	
Area, sq in.	241.9
Aspect ratio	5.81
Airfoil section	NACA 0009
Tip chord, in.	4.60
Root chord, in.	8.3
Span, in.	37.5
Taper ratio	0.55
Sweepback (leading edge), deg	7.3
Mean aerodynamic chord, in.	6.62
Propellers (three blades each):	
Diameter, in.	20
Chord, in.	2.5
Solidity	0.239

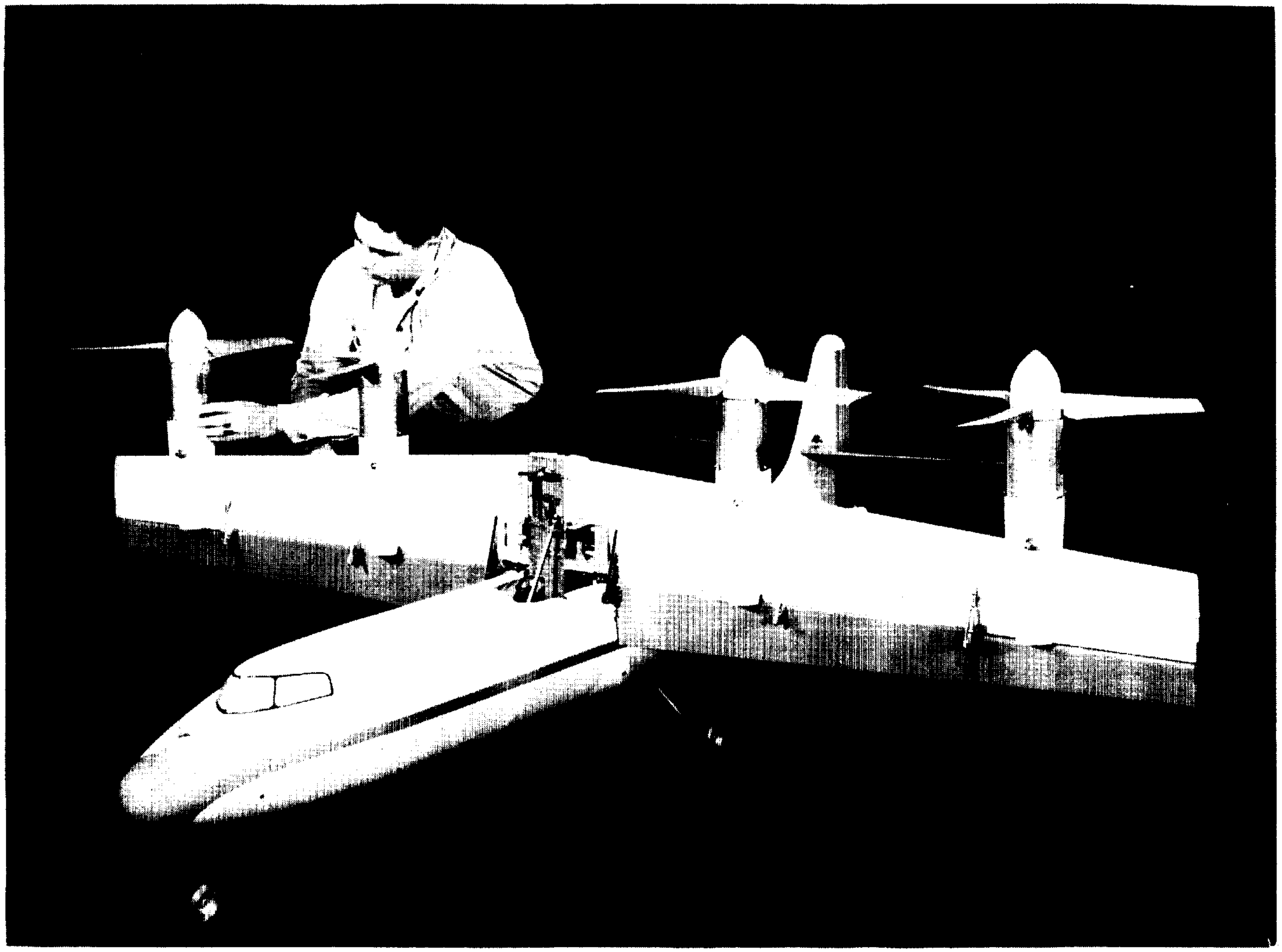

Figure 1.- Photograph of model. L-57-4940.1

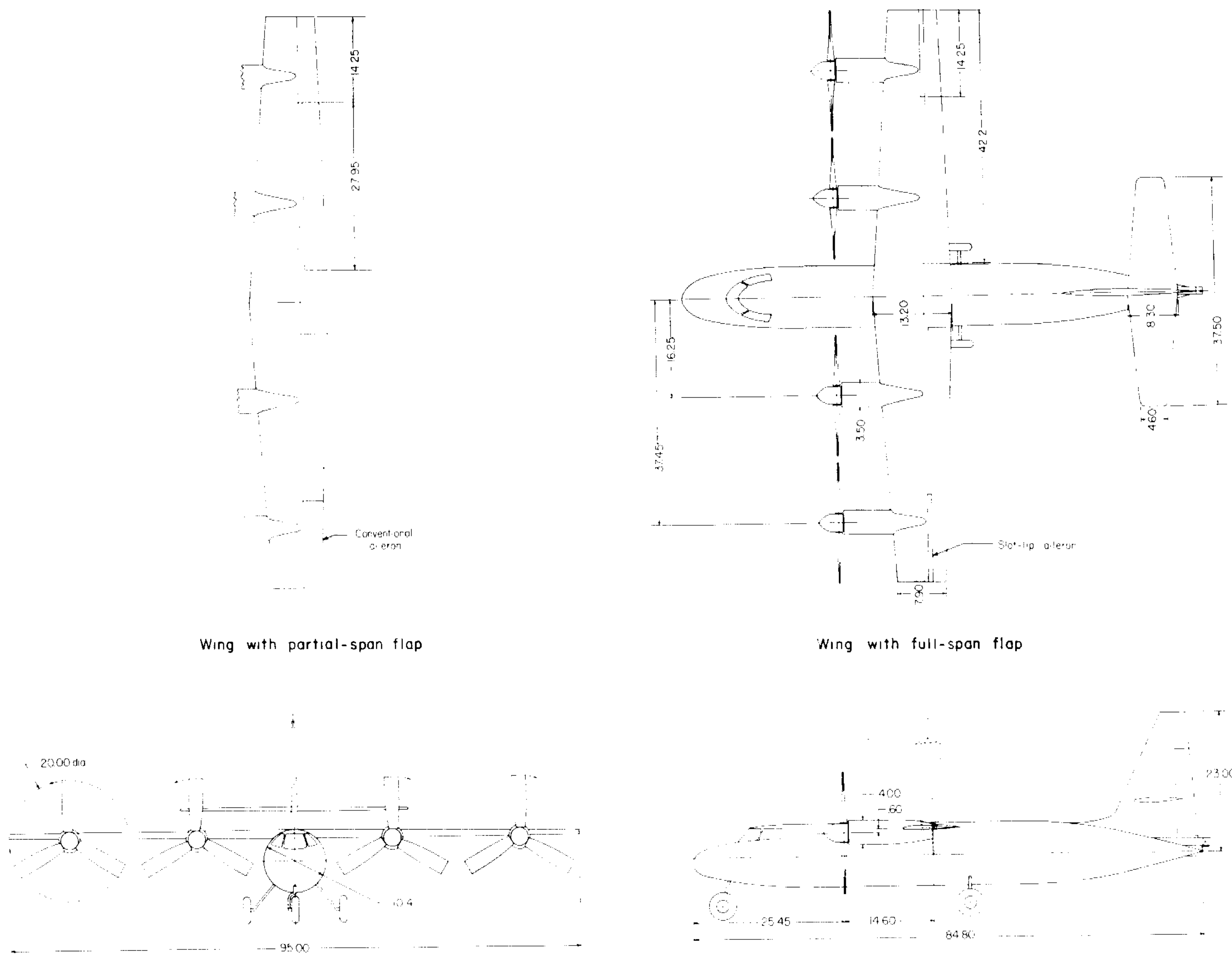

Figure 2.- Sketch of model. All dimensions are in inches.

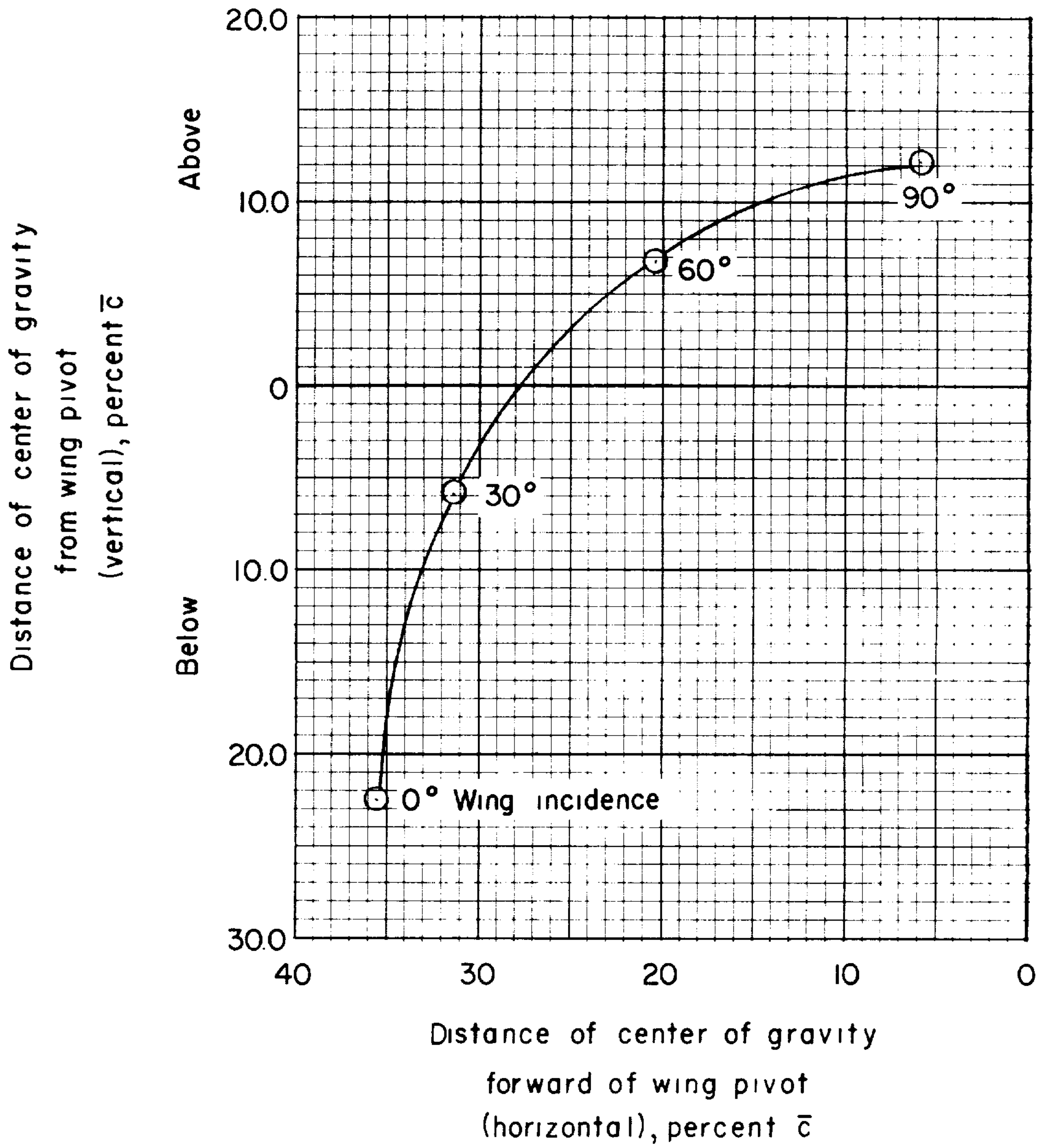

Figure 3.- Variation of model center of gravity with wing incidence.

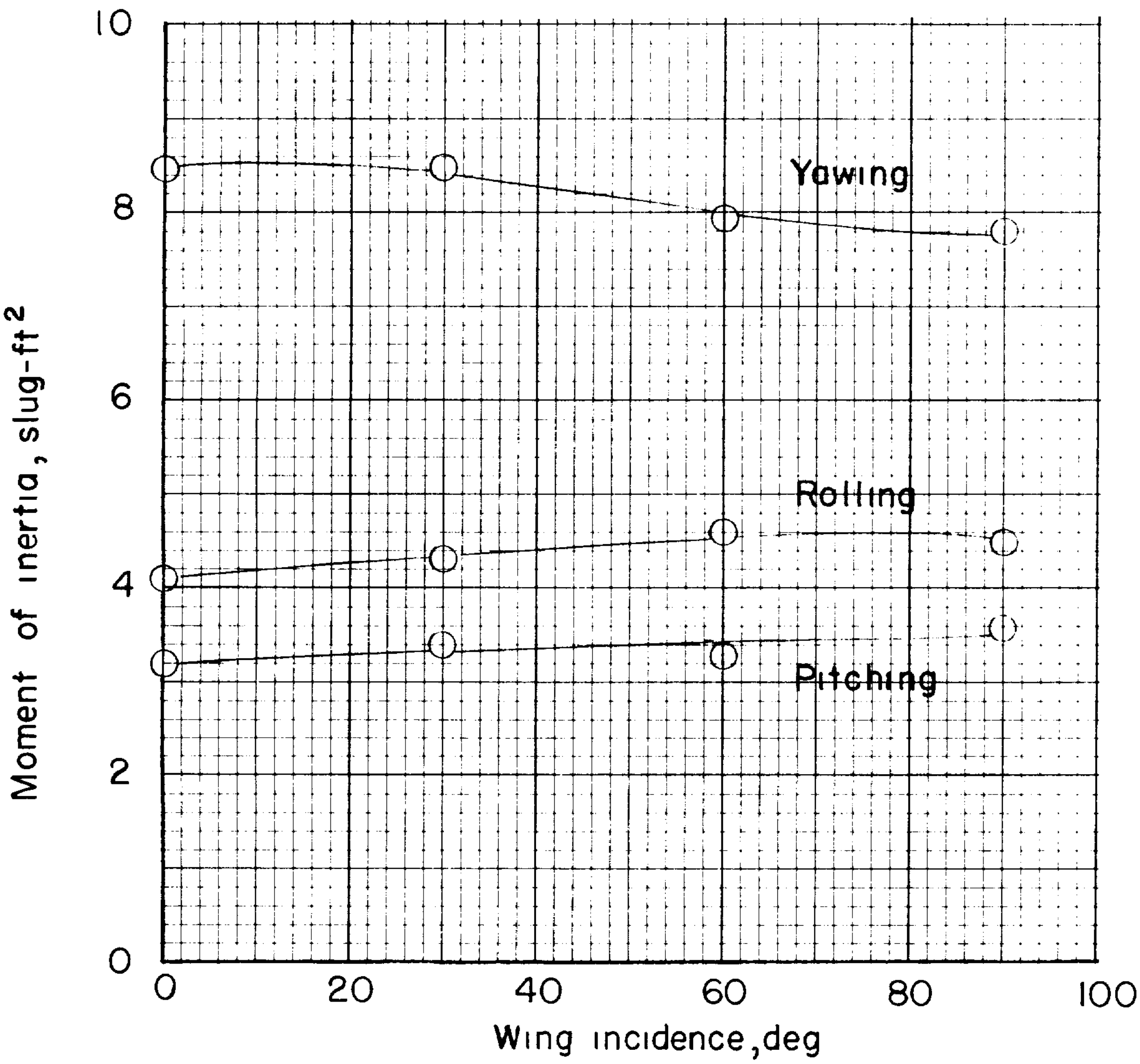

Figure 4.- Variations of moments of inertia with wing incidence about center-of-gravity locations (indicated in fig. 3). Model weight, 51.28 pounds.

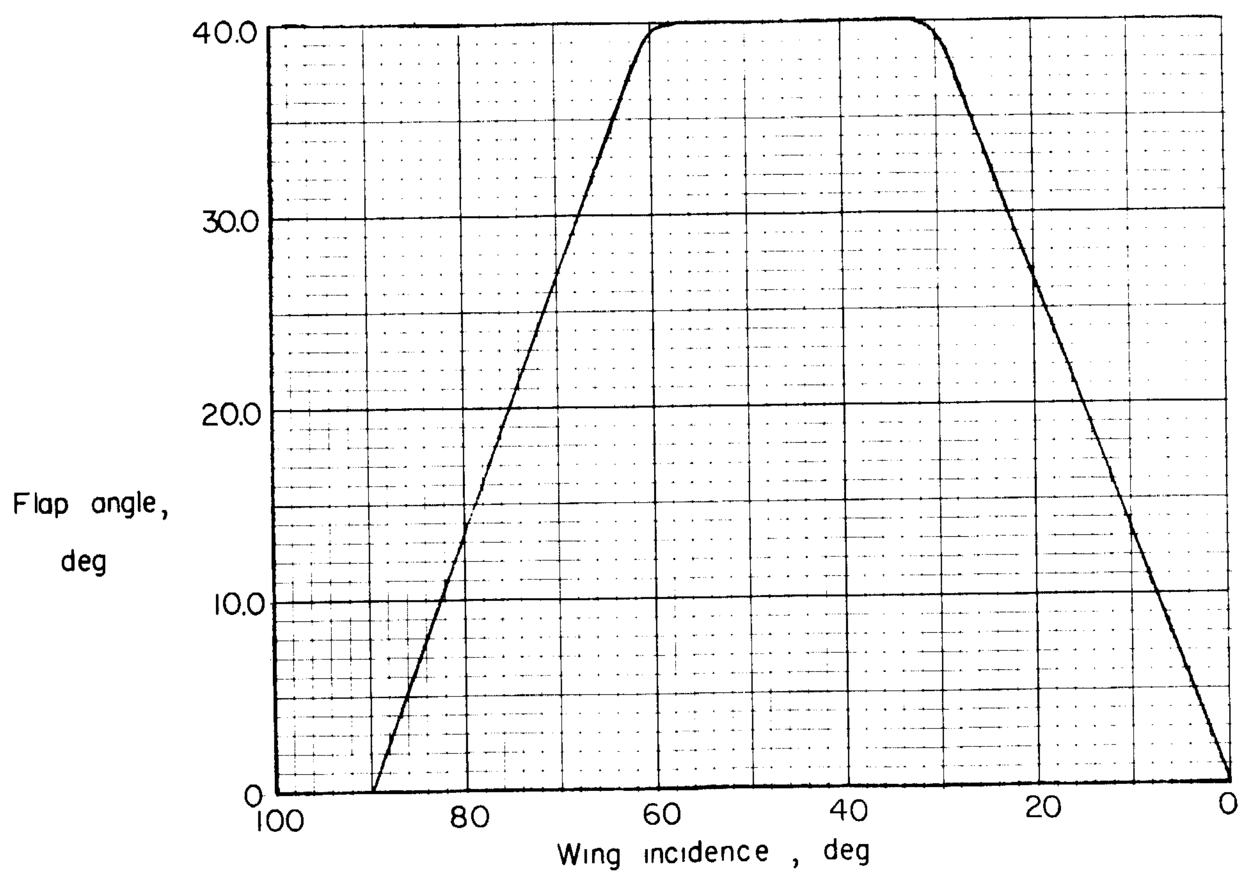

Figure 5.- Variation of model flap angle with wing incidence.

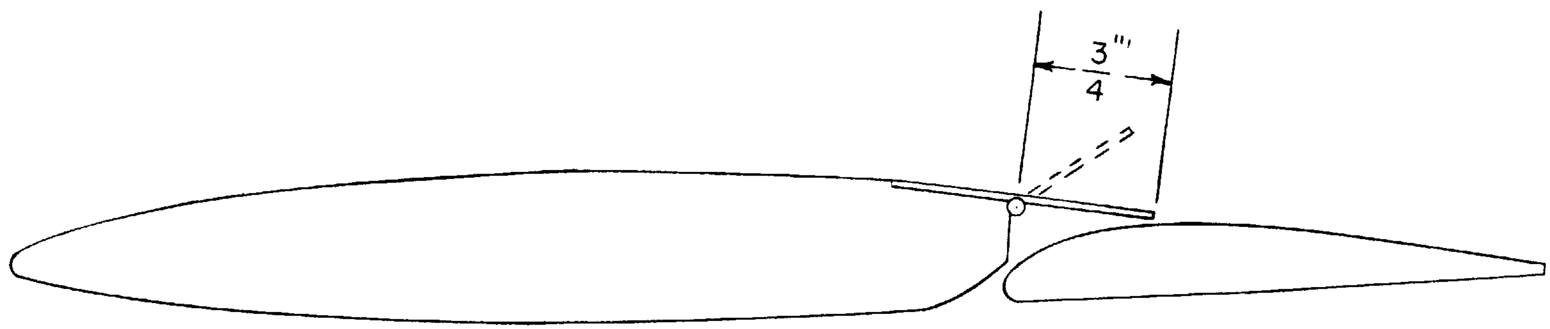

Figure 6.- Typical wing cross section through the slot-lip aileron.

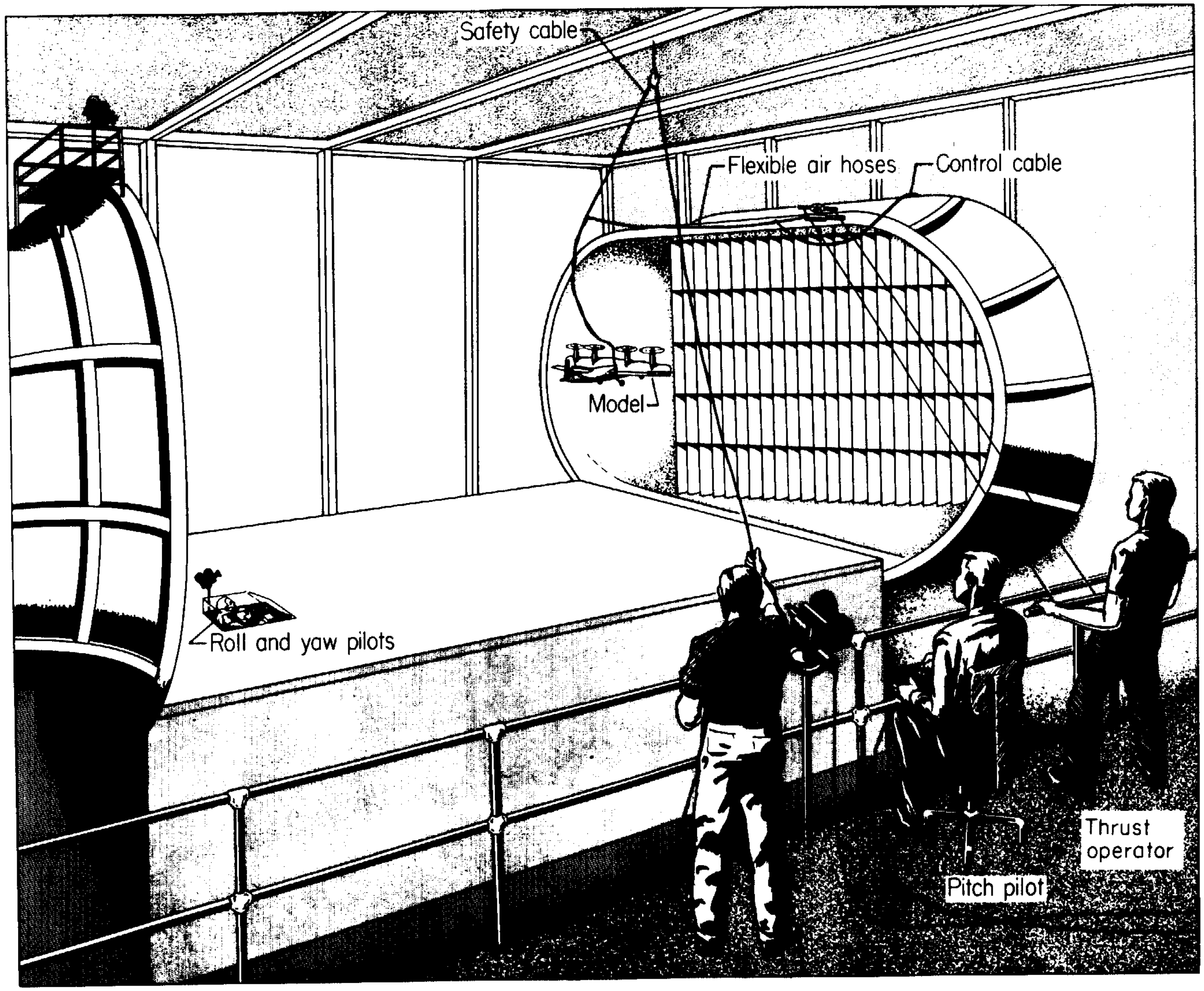

Figure 7.- Sketch of test setup used for transition flight tests. L-61-2837.1

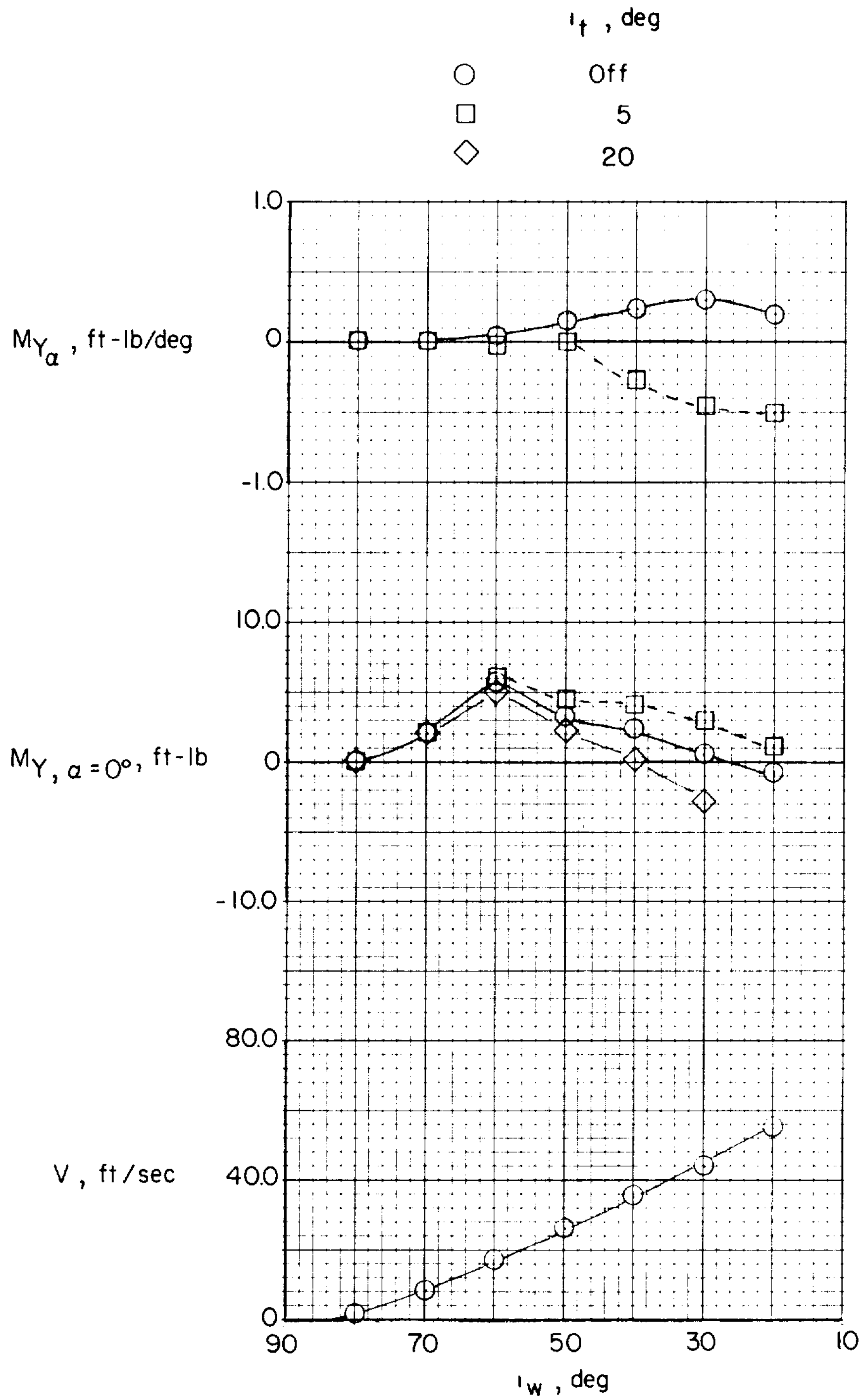

Figure 8.- Variation of longitudinal stability and trim parameters with wing incidence for partial-span-flap configuration with undrooped conventional aileron. (Data from ref. 4.)

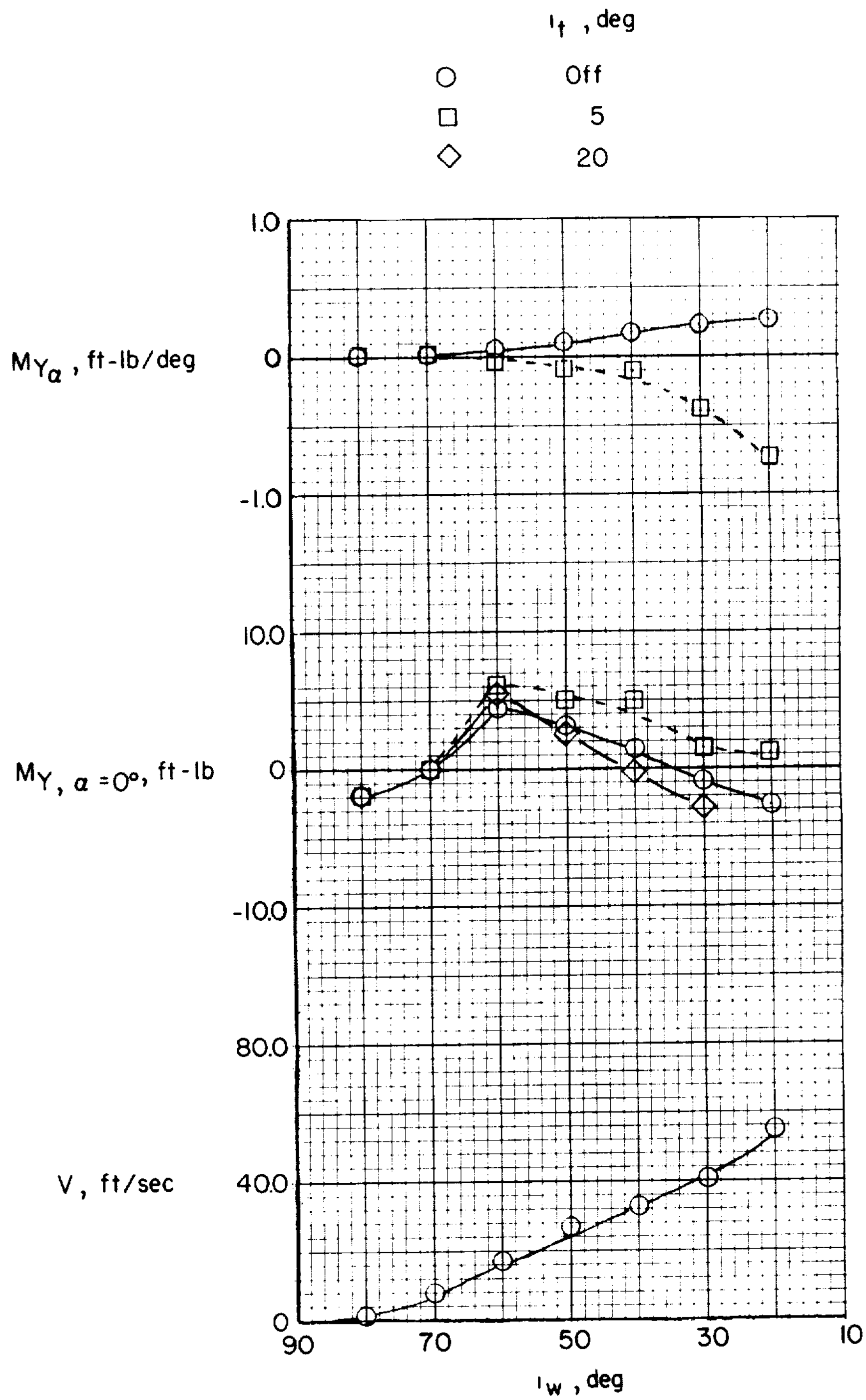

Figure 9.- Variation of longitudinal stability and trim parameters with wing incidence for the partial-span-flap configuration with drooped conventional aileron. (Data from ref. 4.)

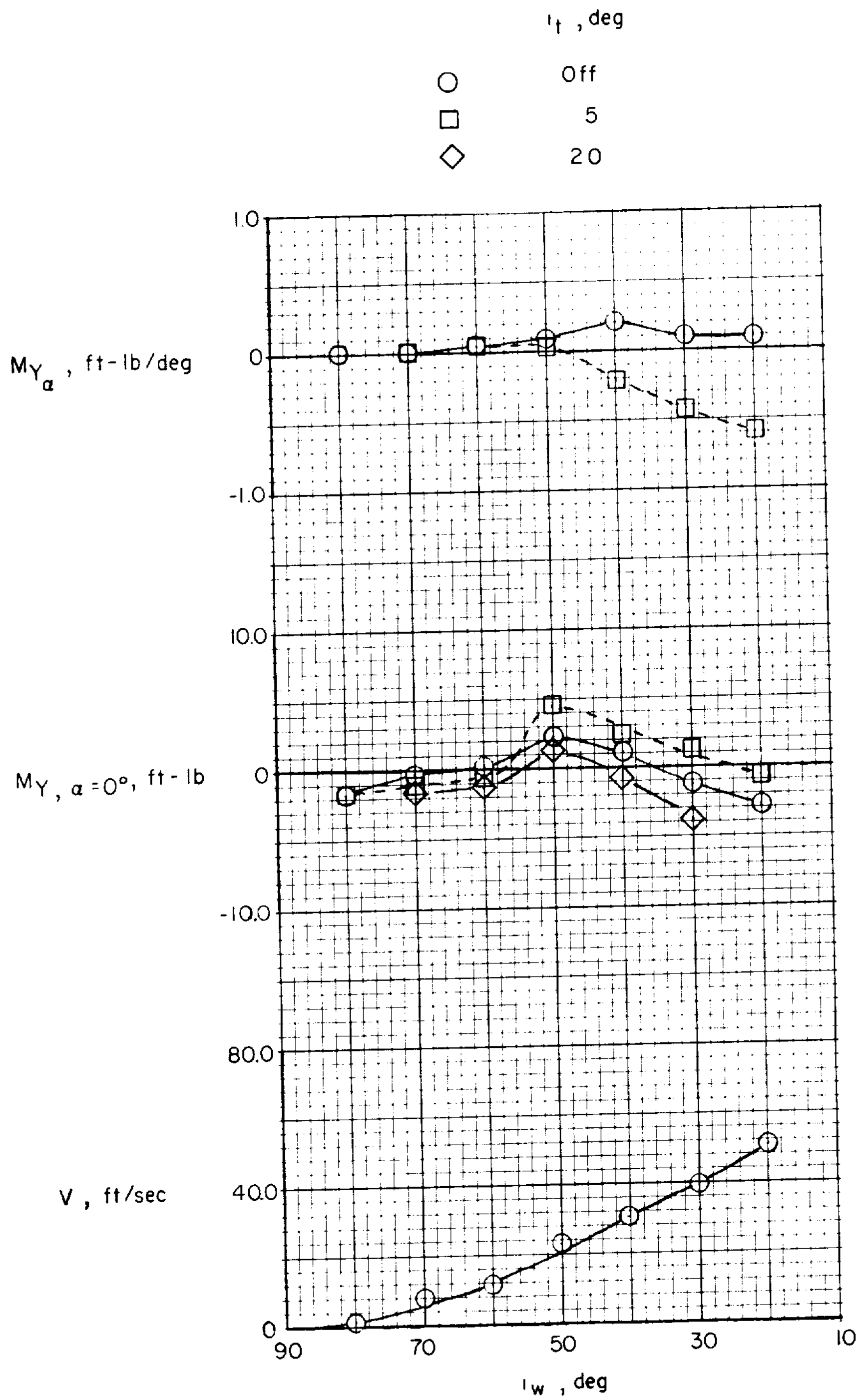

Figure 10.- Variation of longitudinal stability and trim parameters with wing incidence for the full-span-flap configuration with slot-lip aileron. (Data from ref. 4.)

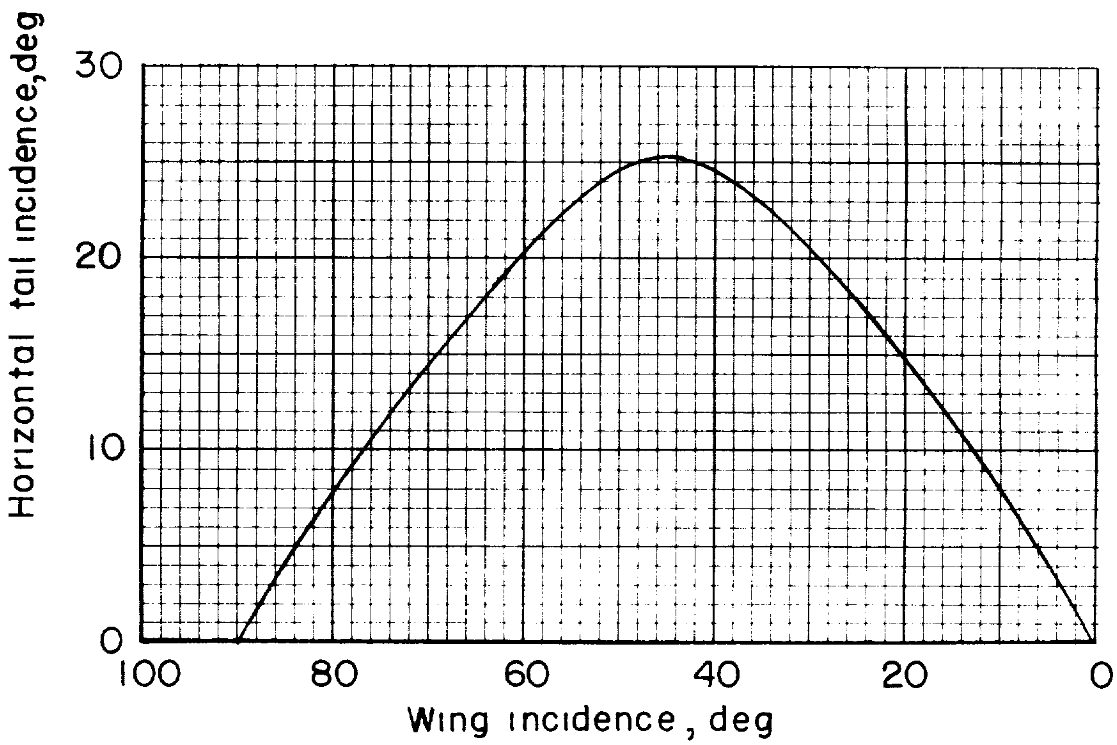

Figure 11.- Variation of horizontal-tail incidence with wing incidence.

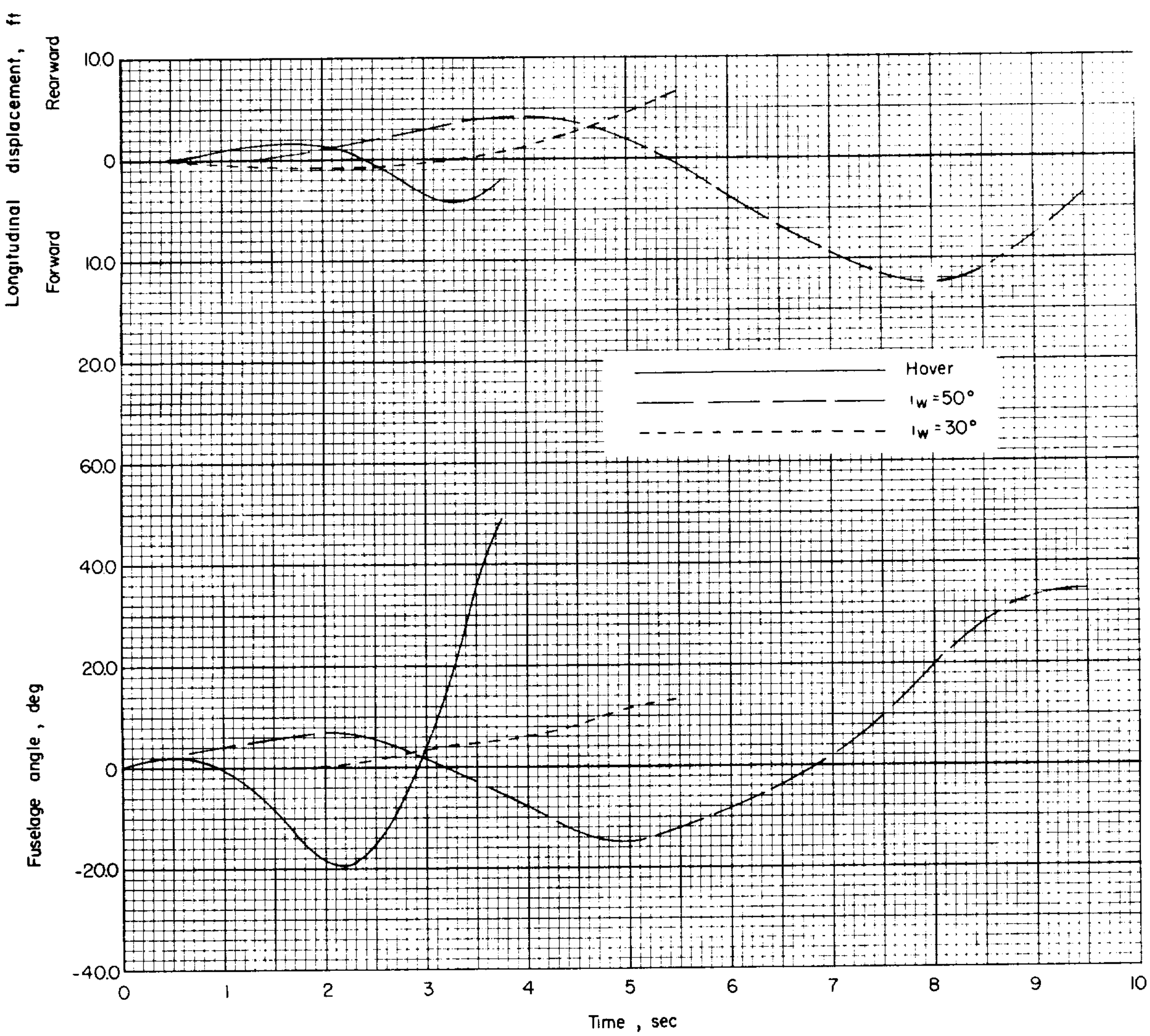

Figure 12.- Uncontrolled pitching motions of the model.

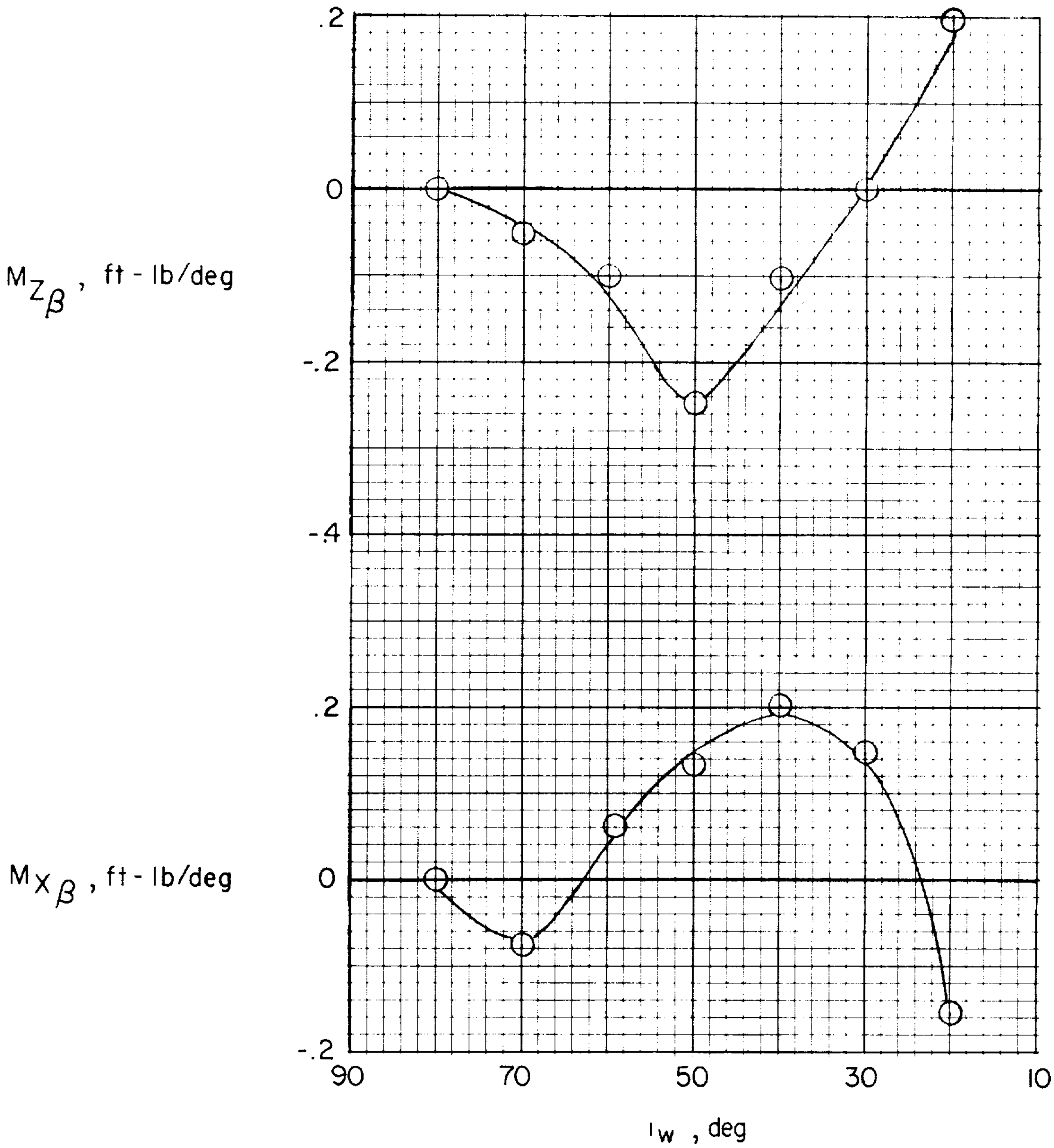

Figure 13.- Variation of directional stability and effective dihedral parameters with wing incidence for the full-span-flap configuration. (Data from ref. 4.)

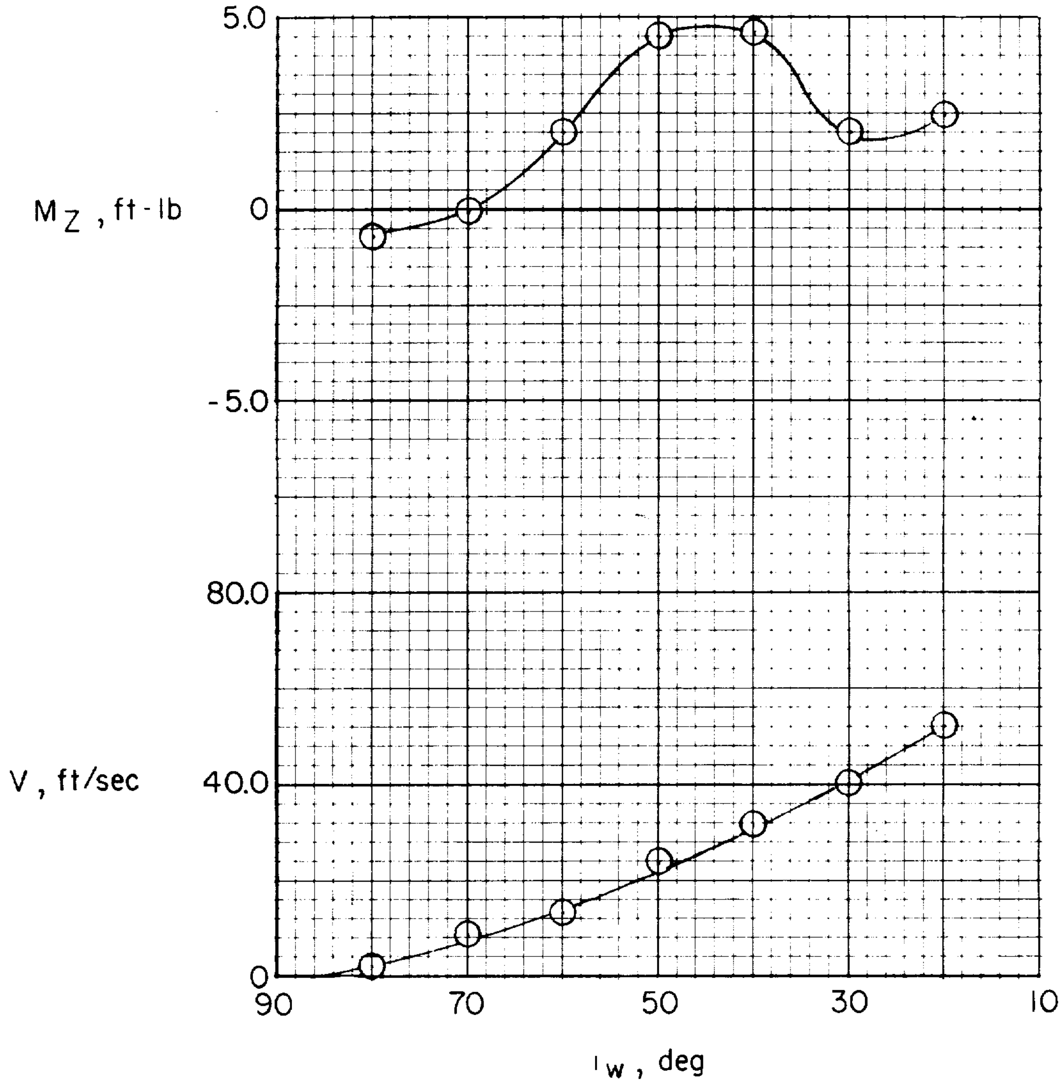

Figure 14.- Variation of yawing moment with wing incidence for the full-span-flap configuration. (Data from ref. 4.)